(2)

Measurement Notes

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A Spiral-Transmission-Line Technique for Detecting Slot Apertures in Shield Enclosures

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Abstract

This note presents another concept, SPIRA, for monitoring the integrity of a shield enclosure. In this concept a helically wound conductor is used as a transmission line in conjunction with the shield enclosure. This type of structure produces an external magnetic field with a strong component parallel to the axis of the helix. This allows the helix to lie parallel to potential slot apertures in the shield enclosure. A similar helix is used on the other side of the shield wall to monitor penetrating magnetic fields.

I. Introduction

Recent papers [5,6] have addressed some techniques for monitoring the integrity of shield enclosures. Considering the possibility of faulty seams and the dominant coupling of the magnetic-field component parallel to thin slots through the seams leads to the SCUTUM concept [5]. In this case conductors are run parallel to the shield surface (both outside and inside) in a direction transverse to the seams. These form transmission lines which give good coupling through the seams (good fault-detection sensitivity) and allow one to locate a fault from the electromagnetic data.

For large penetrations of shield enclosures, such as doors which open and close to allow entrance and exit of large items, the transmission-lines can be rerouted around the penetration [6]. Special exciting and monitoring loops can be placed around a door perimeter if it is the closure of the door as reflected in the electrical connection of the door to the shield enclosure around the door perimeter that one wishes to monitor [6]. Again magnetic-field generators and receivers are chosen with attention paid to the magnetic-field component parallel to the potential slot aperture.

In this paper we explore another technique for monitoring shield enclosures for potential faults in the form of slot apertures. Recognizing that it is the component of the magnetic field parallel to the slot that is important, we need to consider illumination techniques that provide such a field and (by reciprocity) also respond to it. If it is desired that some type of antenna be aligned along the slot (seams between shield panels, door perimeters, etc.) then this should produce and respond to a magnetic field generally parallel to it. This can be done by a helical conductor, in effect a distributed solenoid. This will be considerably more inductive than a single wire parallel to the shield surface, giving a slow-wave structure. In effect this can be considered the distributed version of the magnetic-dipole arrays in [6].

II. Transmission Line Composed of Helical Conductor Over Ground Plane

As indicated in Figure 2.1 let us consider a helix with

$$N' = \frac{1}{\Delta} \text{ turns per unit length}$$
$$\Delta \equiv \text{spacing between turns}$$
$$b \equiv \text{radius of helix}$$
$$a \equiv \text{distance of axis of helix from conducting surface}$$
$$x \equiv \text{coordinate along axis of helix} \tag{2.1}$$

Considering this as a transmission line it has an equivalent circuit

$$L' \equiv \text{inductance per unit length (longitudinal)}$$
$$C' \equiv \text{capacitance per unit length (transverse)}$$
$$V'_s \equiv \text{voltage source per unit length (longitudinal)}$$
$$I'_s \equiv \text{current source per unit length (transverse)} \tag{2.2}$$

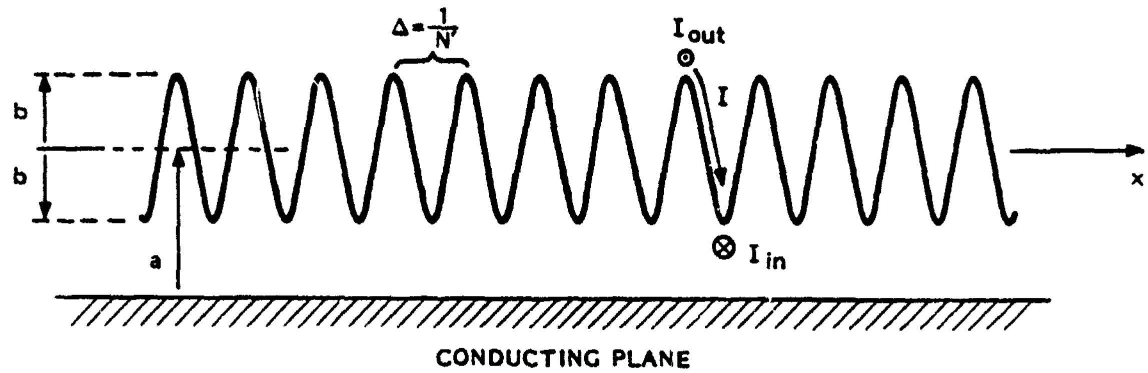
Initially we do not consider the sources, but V'_s is important when such a helix is used to detect the magnetic field on the other side of a slot.

Let us estimate C' by approximating the helix as a conducting cylinder giving [2]

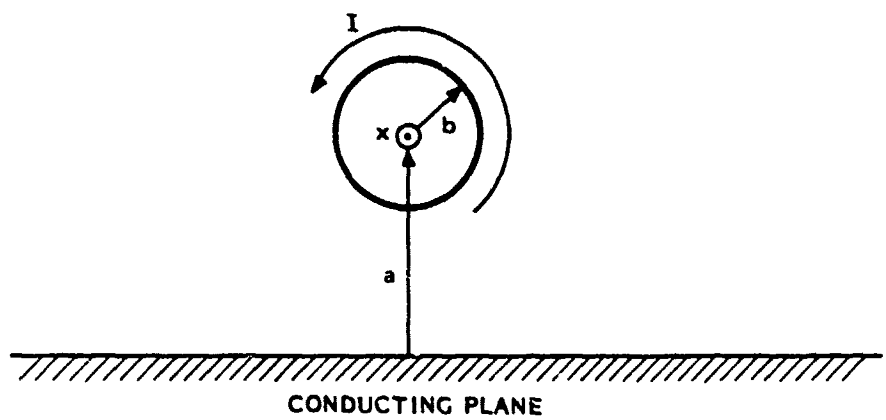
$$C' = \frac{\varepsilon_o}{f_g}$$

$$f_g = \frac{1}{2\pi} \operatorname{arccosh}\left(\frac{a}{b}\right) = \frac{1}{2\pi} \ln\left(\frac{a}{b} + \left[\left(\frac{a}{b}\right)^2 - 1\right]^{1/2}\right) \tag{2.3}$$

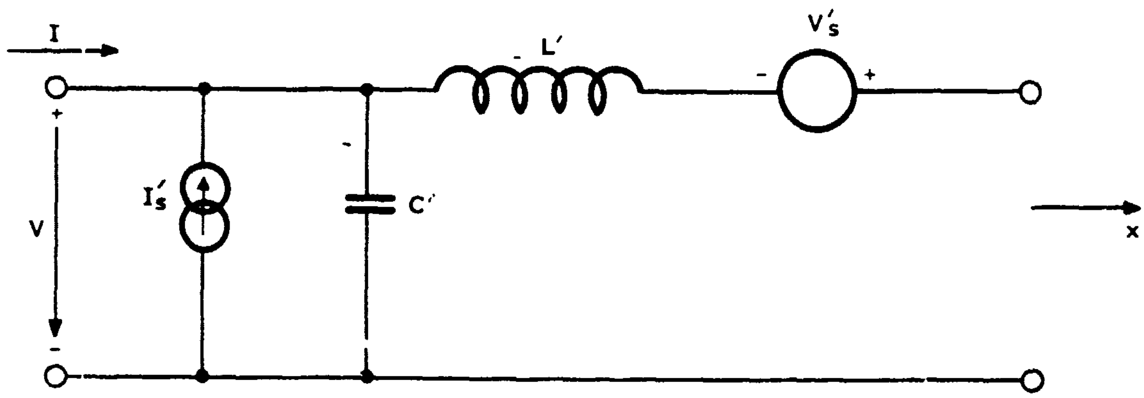
This approximation is valid provided $\Delta \ll b$, otherwise one can reduce the effective value of b, allowing electric flux inside the cylinder. For small Δ/b this correction can be based on a local approximation of the helix as a grid of parallel wires [1].



A. Side View



B. End View



C. Per-Unit-Length equivalent circuit

Figure 2.1 Helical Conductor Over Conducting Plane

Let us write L' as

$$L' = L'_o + L'_s$$

$L'_o \equiv$ inductance per unit length of conducting cylinder above conducting plane.

$L'_s \equiv$ inductance per unit length of solenoid of N' turns per unit length (2.4)

Basically L'_o concerns the magnetic flux outside the solenoid while L'_s concerns that inside. An estimate for L'_o follows the same idea as that for C' in (2.3) giving

$$L'_o = \mu_o f_g \tag{2.5}$$

with f_g approximated as above. As will turn out L'_o is often negligible compared to L'_s.

To estimate L'_s let us use the usual solenoid formula [3] for a solenoid of length ℓ

$$L_s = \mu_o N^2 \frac{\pi b^2}{\ell} f\left(\frac{\ell}{2b}\right)$$

$$f\left(\frac{\ell}{2b}\right) \rightarrow 1 \quad \text{as} \quad \frac{\ell}{2b} \rightarrow \infty \tag{2.6}$$

From [3] one can see how rapidly f approaches 1, e.g., f is .9 for $\ell/(2b)$ between 3 and 4. Then letting $\ell/(2b) \rightarrow \infty$ we have

$$N = N'\ell$$

$$L'_s = \frac{L_s}{\ell} = \mu_o N'^2 \pi b^2 \tag{2.7}$$

For solenoids of general cross sections (not necessarily circular) this generalizes to

$$L'_s = \mu_o N'^2 A$$

$$A \equiv \text{cross-section area of solenoid} \tag{2.8}$$

Since the solenoid is really a helix with spacing Δ between turns the above formulae are approximate. In effect A is increased by increasing a an amount of order Δ[1]. In principle one can use a more detailed calculation accounting for the self and mutual inductances for all the turns such as in [4]. The turn spacing also complicates the separation of L' into external and internal parts as in (2.4). However, the important term for our purposes is L'_s.

As illustrated in Figure 2.1C the telegrapher equations are

$$\frac{\partial V}{\partial x} = - L' \frac{\partial I}{\partial t} + V'_s$$

$$\frac{\partial I}{\partial x} = - C' \frac{\partial V}{\partial t} + I'_s \tag{2.9}$$

For the case of no sources the homogeneous equations have solutions of the well-known form

$$V(x,t) = V_o \, g\left(t \mp \frac{x}{v}\right)$$

$$I(x,t) = \pm \frac{V_o}{Z_c} \, g\left(t \mp \frac{x}{v}\right)$$

$V_o \equiv$ arbitrary constant of dimension volts

$v \equiv$ propagation speed

$= [L'C']^{-1/2}$

$Z_c \equiv$ characteristic impedance

$= \left[\frac{L'}{C'}\right]^{1/2}$

$$g\left(t \mp \frac{x}{v}\right) \equiv \text{dimensionless waveform} \tag{2.10}$$

Here t - x/v gives propagation in the direction of increasing x and conversely.

Using the approximations in (2.8) and neglecting L'_o we have

$$v = \frac{c}{N'} \left[\frac{f_g}{A}\right]^{1/2}$$

$$c \equiv \left[\mu_o \epsilon_o\right]^{-1/2} \equiv \text{speed of light}$$

$$Z_c = Z_o N' \left[f_g A\right]^{1/2}$$

$$Z_o \equiv \left[\frac{\mu_o}{\epsilon_o}\right]^{1/2} \equiv \text{wave impedance of free space} \tag{2.11}$$

Note how the speed is proportional to $1/N'$. Except for a constant this is like the wave is propagating along the helical wire. Note also that for large $N'\sqrt{A}$ we have $v \ll c$ and $Z_c \gg Z_o$.

While the above results indicate a frequency-independent propagation speed, and thereby a dispersionless propagation of pulses, this is only approximate. Note that in (2.6) and (2.7) our solenoid inductance per unit length is a function of $\ell/(2b)$ unless this parameter is large. At high frequencies if the radian wavelength λ on the transmission line is of order of 2b one might expect L'_s to be inaccurately depicted by the above formula. So there may be some dispersion at high frequencies giving a high-frequency limitation to the use of such a transmission line for pulses.

III. Magnetic Field Associated with Transmission-Line Wave

Consider now a step-function wave on the transmission line of the form

$$g\left(t - \frac{x}{v}\right) = u\left(t - \frac{x}{v}\right)$$

$$v \ll c \tag{3.1}$$

As discussed in the previous section there are high-frequency limitations so the step pulse will actually be better considered as one with some non-zero rise time. Behind the wavefront ($x < vt$) there is a magnetic flux

$$\Phi_m = \mu_o N' AI \tag{3.2}$$

contained in the solenoid. In front of the wavefront ($x > vt$) there is (approximately) no magnetic flux. Since $\nabla \cdot \vec{B} = 0$ where did this flux go?

Considering Figure 3.1A and ignoring the conducting plane we have a picture of the magnetic field near the wavefront. Since $v \ll c$ let us consider a quasi-static approximation. Letting all of Φ_m leave the solenoid in the vicinity of $x=vt$ note that for distances large compared to a the solenoid is approximately parallel to the exterior magnetic field. Basically we have the field of an equivalent magnetic charge

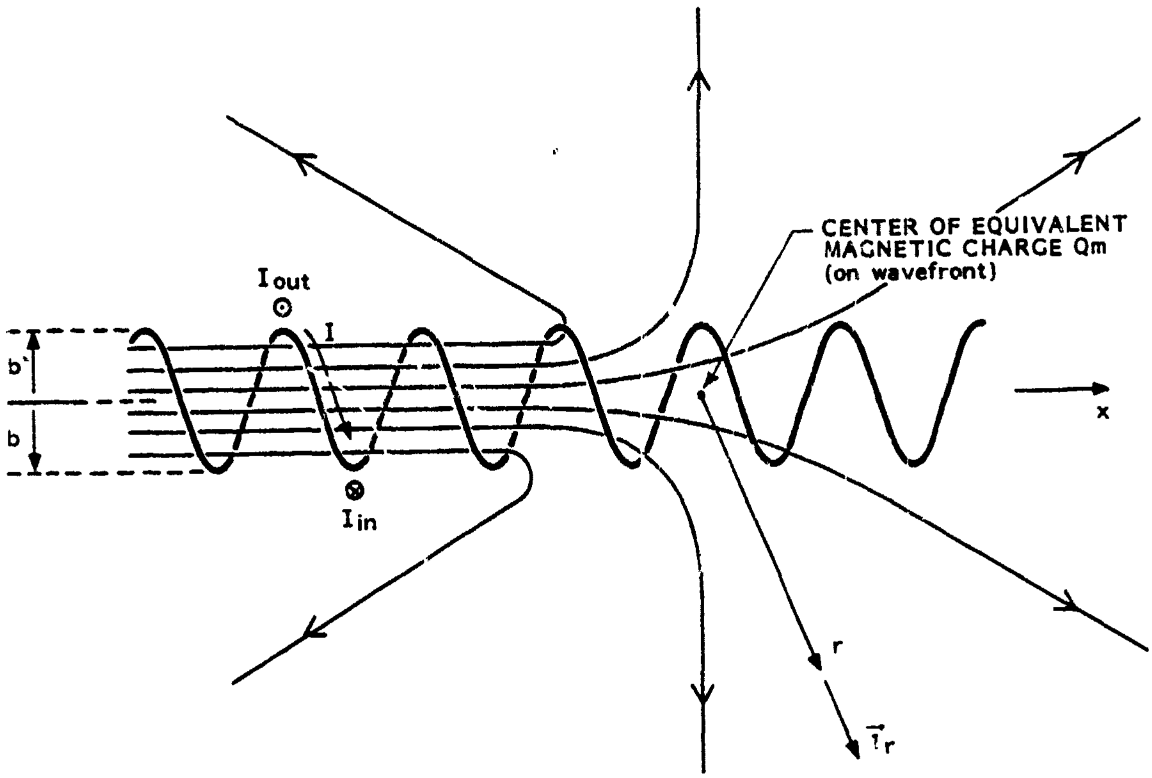
$$Q_m = \Phi_m \tag{3.3}$$

diverging from a "point" in all directions giving

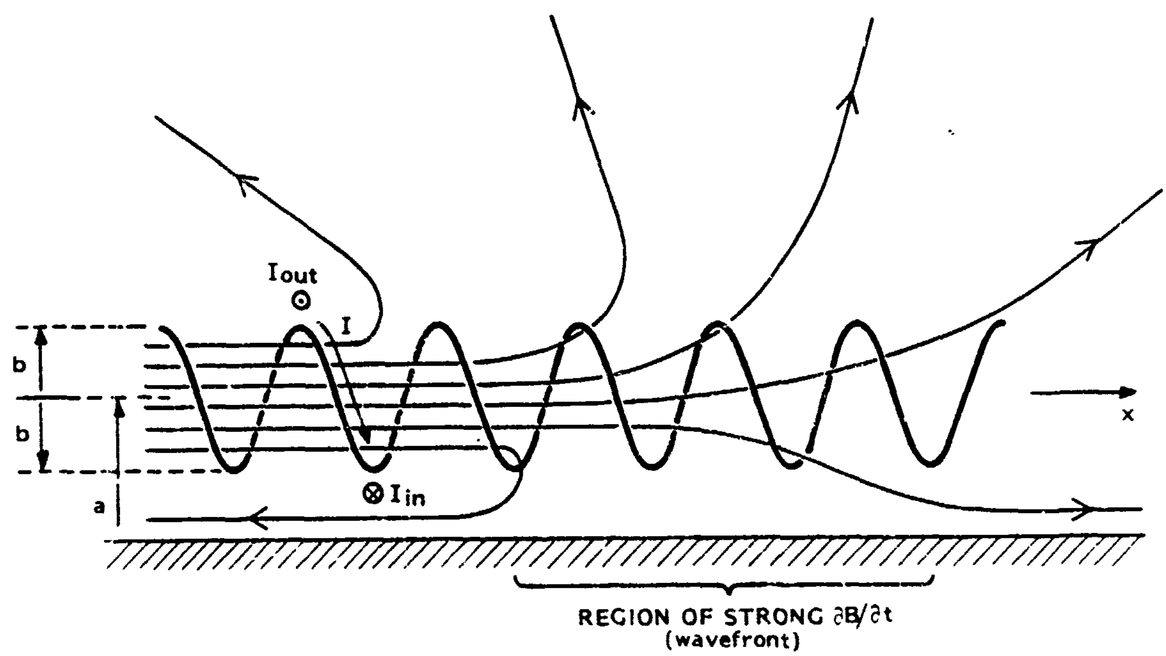
$$\vec{B} = \frac{\Phi_m}{4\pi r^2} \vec{1}_r$$

$\vec{1}_r$ = unit vector in r direction considering wavefront as coordinate origin (3.4)

Since $v \ll c$ this looks like a slowly moving magnetic monopole. Of course the magnetic field lines do not terminate there but go through the solenoid to emerge somewhere else and eventually form closed lines. The term "wormhole" has been used to describe the closure of electric field lines from a positive to a negative charge, this wormhole passing in some higher dimensional space of which our space contains only three of these dimensions [7].



A. Magnetic field exterior to solenoid characterized by equivalent magnetic charge



B. Magnetic field in presence of conducting plane

Figure 3.1 Magnetic Field Produced by a Step-Function Wave on Helical Transmission Line

What we have in our present example might be termed a pseudo magnetic wormhole. The magnetic flux lines return (out of our sight, confined to the solenoid), but still in three dimensional space. The surface integral to find the enclosed magnetic charge via Gauss' theorem has to include a contribution from the flux in the solenoid which will result in zero magnetic charge.

Now since the solenoid is near and parallel to a conducting plane we need an image a distance a on the other side of the plane. This also has an equivalent magnetic charge of the same sign giving a total equivalent magnetic charge of $2Q_m$. Including the image let us look at positions along the conducting surface directly between the solenoid and its image. For this we have

$$r = |x - vt|$$

$$B_s \simeq \frac{2Q_m}{4\pi} \frac{\text{sign}\,[x-vt]}{[x-vt]^2} = \mu_o \frac{I\,N'A}{2\pi} \frac{\text{sign}\,[x-vt]}{[x-vt]^2}$$

$$\frac{\partial B_s}{\partial t} = \mu_o \frac{Q_m v}{\pi} \frac{\text{sign}\,[x-vt]}{[x-vt]^3} \tag{3.5}$$

Note that there is no singularity at $x=vt$ since we should ascribe some minimum value to $|x-vt|$, say of the order of a, for these purposes. In any event a pulse of $\partial B_s/\partial t$ (like a broadened delta function for a step pulse on the transmission line) passes over the conducting surface at speed v searching out slots parallel to the solenoid axis. This pulse is significant over distances of some constant times a, and is the region of strong external magnetic field in Figure 3.1B. Note that high-frequency dispersion can also spread out this pulse somewhat.

If a slot aperture is encountered then magnetic field will penetrate say producing $B_{through}$ on the second side of the conducting surface along the axis of the receiving helical transmission line. This second transmission line is characterized much as the first as in (2.9). The per-unit-length source is just a voltage type with

$$V_s' = N'A \frac{\partial}{\partial t} B_{through} \tag{3.6}$$

with N' and A characteristic of this second helical transmission line.

IV. Concluding Remarks

This type of helical transmission line has interesting properties which allow its use for slot-like apertures. The transmitting and receiving helices need to be positioned along (parallel to) potential slots on opposite sides of the shield wall. Potential slots include faults in seams joining shield panels, and faults in the closure of various hatch-like penetrations such as doors around the door perimeter. In the latter case one can mount the helical structure to the shield wall just adjacent to the penetration perimeter.

It would seem such a technique needs a distinctive name. In this case we have slow-propagating, I-revolving antenna or SPIRA (the Latin word for helix or spiral).

References

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